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Mitigation of adverse environmental effects on lunar-based astronomical instruments

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ABSTRACT

The galactic cosmic-ray flux incident on the Moon was examined for its potential adverse impact on the performance of the large lunar telescope (LLT) proposed as a part of NASA's Space Exploration Initiative (SEI). Noise produced by the cosmic-ray flux in the charge coupled devices (CCD's) to be used as the primary photodetector in the telescope was estimated. It was calculated that approximately 2.5 m of regolith would provide the shielding necessary to reduce the noise to an acceptable level.

Dust is an omnipresent environmental concern for any human-assisted or robotic scientific instruments deployed on the Moon. The degree to which dust poses an operational risk to the telescope was examined. Three potential methods for reducing this risk were identified: locating scientific instruments at remote locations; utilizing a prepared, dust-free site for all rocket activities; and covering the optics during high-risk times.

INTRODUCTION

Several astronomical instruments are being considered for deployment on the Moon as part of the SEI. The Marshall Space Flight Center (MSFC) is examining the feasibility of placing a 16-m diameter optical telescope on the Moon in the next century as a potential follow-on to the Hubble space telescope (HST).[1] The LLT will utilize segmented optics and operate in the ultraviolet-visible-infrared portions of the electromagnetic spectrum.

Lunar-based astronomical instruments such as the LLT will be exposed to a solar and galactic cosmic ray (GCR) environment which is much more severe than that present on the Earth or in low-Earth orbit (LEO). The Moon is located outside the Earth's protective atmospheric envelope which acts as a thick shield for highly energetic cosmic-ray particles from space. The Moon also lacks the benefit of the Earth's geomagnetic field, which serves to deflect all but the most energetic cosmic rays away from the planet's surface. Cosmic rays, which are highly energetic and very penetrating, are of significant concern due to their potential impact on the lifetime of and the noise produced in the CCD's likely to be used in lunar-based astronomical instruments.[2]

The dust- and regolith-covered lunar surface will also pose an environmental risk to the telescope and other optical instruments. Human activity will disturb the dust to varying degrees: simple walking can kick up dust that will settle many meters from where it is lofted, while rockets descending to the surface can give small particles ballistic trajectories with sufficient velocity to reach the other side of the Moon! If such dust is permitted to land uninhibited on exposed optical surfaces, the result can be significant degradation of telescope performance.

THE COSMIC-RAY ENVIRONMENT

GCR's are composed primarily of hydrogen and helium ions (protons and alpha particles), although other ions are also present (Fig. 1).[3] These high-energy, highly penetrating ions, and the secondary particles they generate by nuclear collisions, can deposit energy by ionization in passing through a CCD array and release free electrons, which is read by the CCD as noise. During the projected lifetime of these lunar-based instruments, a significant number of nuclear interactions may also be produced within the CCD, causing displacement damage and degradation of performance that can lead to the need for CCD replacement.

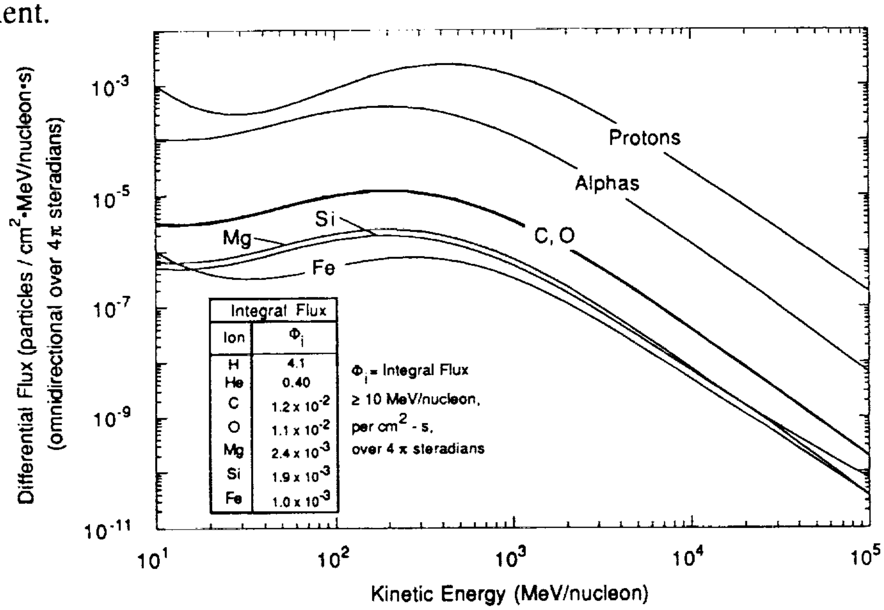

Fig. 1. Galactic cosmic-ray spectra at solar minimum, based on data compilation by Adams.

An additional component of the cosmic-ray flux incident on the Moon is the radiation of solar origin. Although the Sun is constantly emitting low-energy solar wind particles, the flux is small until the advent of a solar flare, during which the particle emission can increase by orders of magnitude. However, these relatively low-energy solar cosmic-ray particles are much more easily shielded than the penetrating galactic cosmic rays and are typically present for such a relatively short period of time that they are not considered to be a major problem.

The feasibility of using lunar regolith to shield CCD's and reduce the galactic cosmic-ray induced noise to acceptable levels was investigated. Calculations using detailed Monte Carlo radiation transport codes that take into account secondary particle production were performed to determine the radiation environment as a function of depth in lunar regolith. The predicted depth-dependent fluxes are shown in Fig. 2.[4] For CCD noise assessments, it is the ionization produced by the charged particle flux that is important. The probability of a noise event from a nuclear collision by the neutral particles (neutrons and gamma rays) is relatively small due to the small thickness of the CCD's. Figure 2 also shows that the most abundant charged particle in the lunar cosmic-ray environment is electrons, whereas protons dominate the background for satellite observatories in LEO and muons are the most prevalent particle type in the sea-level cosmic-ray background on Earth. Thus, electrons would be the most appropriate particle for irradiations in laboratory tests of CCD noise for lunar applications. The CCD radiation damage by displacement in a shielded lunar environment will be dominated by neutrons.

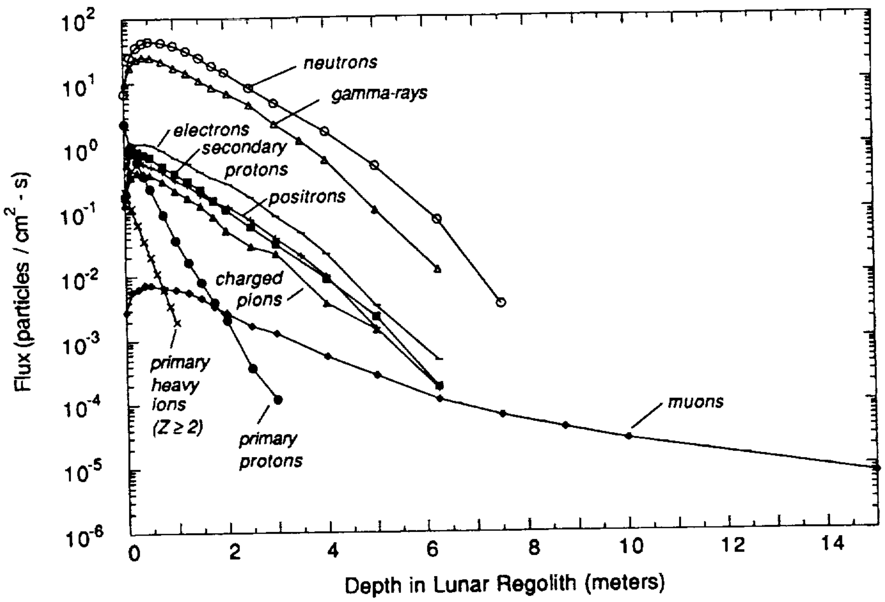

Fig. 2. Predicted radiation environment below lunar surface due to cosmic-ray bombardment.

The shielding needed to reduce the cosmic-ray background to acceptable noise levels for CCD's was parameterized in terms of pixel size and exposure time (Fig. 3). For nominal criteria based on Earth astronomy procedures (1-h exposures and a noise event probability of $<10^{-3}$ per pixel), and assuming a CCD pixel size based on current technology (10 microns by 10 microns), a shielding thickness of about 2.5 m of lunar regolith is obtained. For the baseline LLT design, a buried instrument chamber utilizing this regolith shielding (illustrated in Fig. 4) was selected.[5] The actual shielding needed may well be less than for these particular parameter assumptions; however, more definitive estimates depend on several evolving factors, such as CCD characteristics (pixel sizes, detection sensitivity) and operational considerations (appropriate exposure times). Also, noise reduction techniques, such as signal processing to discriminate between signal versus noise based on spatial and amplitude features, may be able to further reduce the shielding needed. The lunar radiation environment results calculated here will allow revised CCD noise assessments to be performed as these factors become better defined in the future.

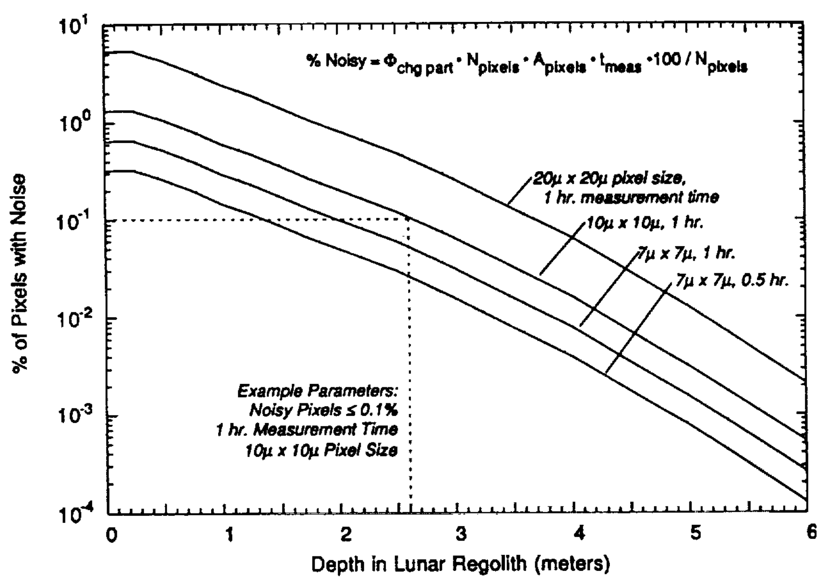

Fig. 3. Lunar regolith shielding needed to reduce CCD noise from cosmic rays.

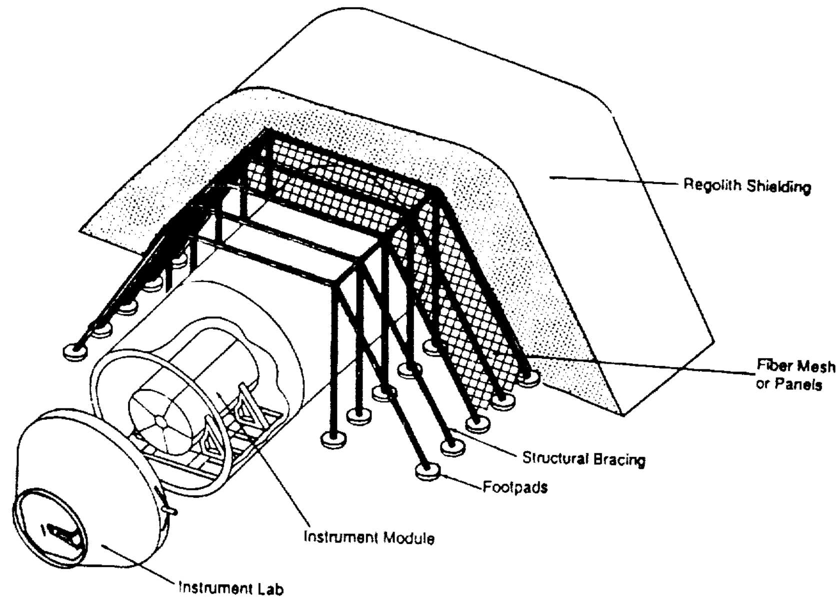

Fig. 4. LLT regolith-covered instrument laboratory concept.

THE DUST ENVIRONMENT

While the unpopulated Moon provides an excellent platform for large, high-resolution astronomical instruments, the presence of humans there may have a significant negative impact on both the instruments and the observations to be made with them. The Apollo missions have shown that human activity can easily disturb lunar dust and, due to the low lunar gravity and negligible atmosphere, can launch even the smallest grains in ballistic paths that stretch far across the lunar surface.[6] The lofted dust may thus be transferred onto the telescope, obscuring the sensitive optics, scattering light resulting in distorted observations, and potentially interfering with the mechanical devices that slew and guide the telescope.

Figure 5 illustrates the range that a ballistic particle may travel on the Moon as a function of its initial velocity. Human endeavors on the Moon will loft dust particles with velocities comparable to those given in Table I and labeled in Fig. 5.[7] All human activity, from launching rockets to simply walking on the lunar surface, will spread dust to considerable distances.

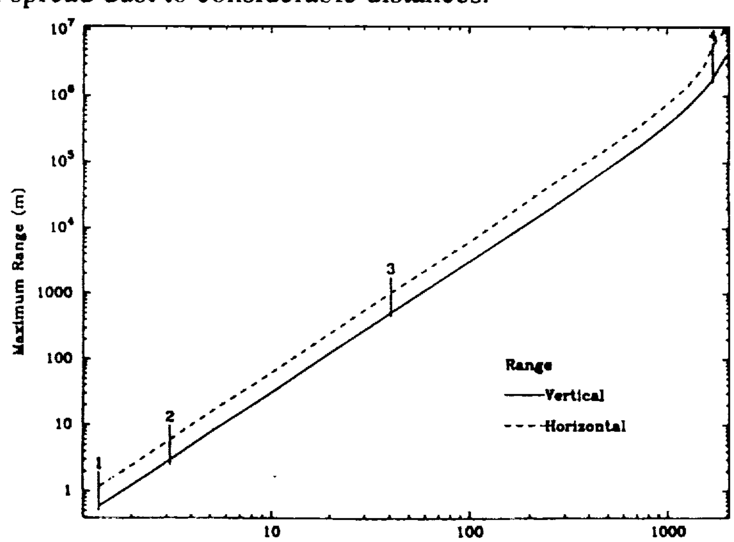

Fig. 5. Plot of the maximum horizontal and vertical range of a lunar particle as a function of its initial speed. The four labeled vertical ticks are those points listed in Table I.

Table I. Speeds of some typical human activities and the maximum horizontal and vertical ranges of particles ejected at these speeds on the Moon.

	Maximum Range (m)		
Activity	Speed	Vertical	Horizontal
1. Driving a vehicle at 5 km/h	1.38	0.59	1.17
2. Dropping a tool from 3 m	3.12	3.00	6.00
3. Throwing a major league fastball	40.7	511	1,023
4. Landing a rocket (rocket exhaust speed)	1,700	1,740,000	5,460,000

The data shown in Table I and Fig. 5 indicate that the most common lunar surface activities will scatter dust no further than approximately 1 km from its lofting point. The data also show that the dust raised by the descent or ascent of a typical rocket can travel as far as the other side of the Moon, leaving no lunar location completely free of the settling dust. Since dust cannot simply be avoided, the quantity accumulated at different locations was assessed in order to determine what distance from a human settlement a telescope must be placed to provide a tolerable dust environment for its optics and mechanisms.

The distribution of dust raised from a nominal rocket landing was estimated based on astronauts' measurements of the crater created by the Apollo 14 lunar lander. These measurements are listed in Table II.[8] From the calculated dust distribution, the obscuration (i.e., the fraction of a surface's area covered by dust) caused by the settling particles was estimated from geometric considerations. The resulting obscuration as a function of horizontal distance from the landing site is plotted in Fig. 6. As a reference, the allowed contamination level for the IRAS and EOS optical instruments is also shown.[9] In order to prevent significant obscuration of the LLT optics by a single rocket landing, the telescope should be located more than 1 km from the rocket landing site. Since several such landings and launches will occur during the lifetime of the LLT, it would seem that the telescope should be moved even farther from the lunar base. However, the need for power and other logistical support from the base will require that the telescope be placed within a few kilometers of it and the landing site. This scenario will require some method of reducing the amount of dust reaching the telescope's optics.

Table II. Data from Apollo 14 landing site.

Crater Diameter	4 m
Crater Depth	10 cm
Crater Volume	1.23 m^3
Approximate Rocket Velocity	1.0 to 1.7 km/s
Assumed Dust Diameter	20 microns

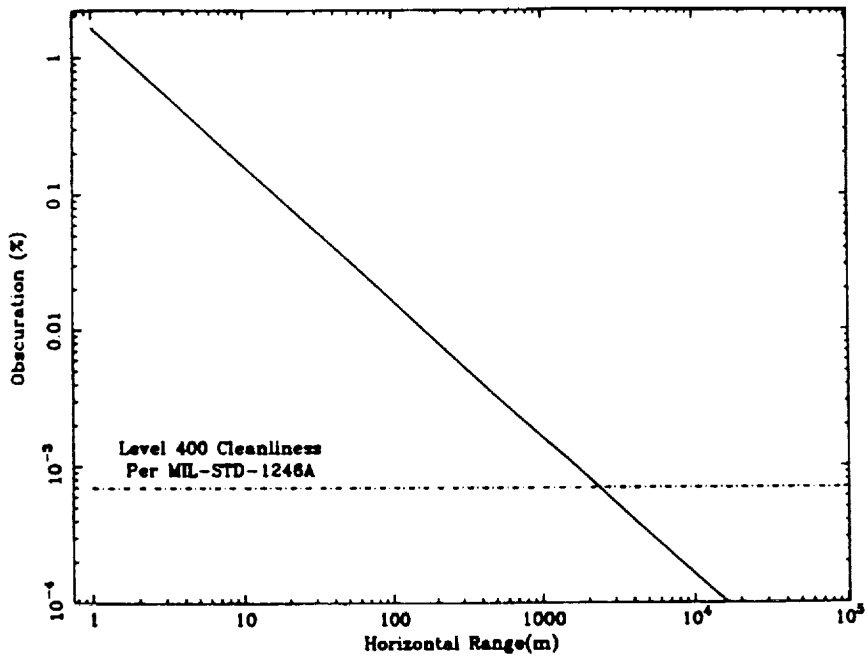

Fig. 6. Plot of the obscuration of a clean surface by dust as a function of distance from the landing site of an Apollo 14-class rocket.

One possible method of reducing dust contamination is to cover the optics during rocket launches and landings, which are the only times that dust from the lunar base is likely to reach the telescope. This would allow the LLT to be located approximately 1 km from the base and would not significantly affect its observing time, since launches and landings will occur relatively infrequently (approximately once per year, probably during daylight hours when no observations are planned). It was estimated that the dust raised by rocket exhaust will remain aloft for less than 1 h. Similar covers proposed as thermal shields may also provide the added benefit of dust protection.[10] However, it should be noted that erecting a large dust cover could significantly increase the mass and transportation cost of the telescope.

Another potential dust-reduction method is to prepare a hard, dust-free site for rocket launches and landings. Such a prepared site would protect not only the LLT, but other scientific instruments as well. However, as the human presence on the Moon expands, it is likely that other projects will require remote, and thus unprepared, landing sites that would be a source of potential dust contamination to the optics of the LLT.

It is recommended that a combination of the techniques mentioned above be used to reduce the threat dust presents to the operation of the telescope. Locating the telescope 1 to 10 km from the base, utilizing a prepared landing site whenever possible, and covering the optics with a thermal shield designed to also serve as a dust cover should reduce the overall risk of dust contamination for the LLT optics. A trade study is suggested to quantify the risk to the optics when only a subset of these proposed techniques be used.

CONCLUSIONS

Reductions in the noise level produced when solar and galactic cosmic rays impinge the LLT CCD arrays can be achieved with a moderate amount of regolith shielding (approximately 2.5 m). The shielding serves to attenuate the highly energetic galactic cosmic rays and reduce the number of secondary particles created by their interaction with the shielding itself. Advances in CCD design and signal processing might provide better noise-rejection and thus reduce the amount of shielding required. Reducing the amount of disturbed lunar dust falling onto the optics of the telescope is not so easily achieved. A combination of locating the telescope at least 1 km from the human outpost, providing a hardened rocket launch/landing pad, and covering the exposed optics should be considered.

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